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MINERALOGICAL AND CHEMICAL INVESTIGATION OF CORES FROM PIEZOMETRIC SITES IN WAITE AMULET TAILINGS, NORANDA, QUEBEC

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MINERALOGICAL AND CHEMICAL INVESTIGATION OF CORES FROM PIEZOMETRIC SITES IN WAITE AMULET TAILINGS, NORANDA, QUEBEC

by

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ABSTRACT

Polished-section microscopy of tailings samples from the saturated zone adjacent to 31 piezometric sites in the Waite Amulet tailings pile shows that the amount of in-situ alteration of pyrrhotite and other sulphides is negligible. In several samples the bulk of the unaltered sulphide grains is accompanied by sparse, variously altered pyrrhotite grains which are interpreted to have been attacked by local surface oxidation during minor interruptions in the more than 30-year accumulation of the tailings pile. Chemical analyses of all of the tailings samples indicate that in most the water-soluble sulphate fraction is less than 1 wt % SO_4, and most of this sulphate is bound as $CaSO_4.nH_2O$. Sulphate which is not water-soluble exceeds 0.3 wt % SO_4 in only 3 samples, and in 2 of these the presence of jarosite has been confirmed by X-ray powder-diffraction patterns. The average value of 0.27 wt % elemental sulphur in the 31 samples is interpreted to be representative of background sulphur rather than an indication of alteration-derived sulphur.

KEYWORDS: sulphide-rich tailings, mineralogy, chemistry, sulphur, water-soluble sulphate, total sulphate, Waite Amulet, Quebec.

ANALYSE MINERALOGIQUE ET CHIMIQUE DE CAROTTES PROVENANT DE SITES PIEZOMETRIQUES DANS LES RESIDUS DE WAITE AMULET A NORANDA (QUEBEC)

par

J.L. Jambor

RESUME

L'analyse microscopique de lames polies d'échantillons prélevés dans les résidus de Waite Amulet révèle que l'altération de la pyrrhotite et d'autres sulfures y est négligeable. Dans plusieurs échantillons, la majorité des grains de sulfure non altérés voisinent des grains épars de pyrrhotite ayant subi diverses altérations probablement causées par une oxydation superficielle locale qui se serait produite au cours d'interruptions mineures de l'empilement des résidus qui aurait duré plus de 30 ans. L'analyse chimique de tous les échantillons de résidus indique que dans la plupart d'entre eux la fraction de sulphate soluble dans l'eau est inférieure à 1 % de SO_4 (en poids) et que la plupart de ce sulphate se présente sous la forme de $CaSO_4.NH_2O$. Le sulphate qui est non soluble dans l'eau ne dépasse 0,3 % de SO_4 (en poids) que dans trois échantillons, et dans deux d'entre eux, réduits en poudre, la présence de jarosite a été confirmée par la diffraction des rayons X. La teneur moyenne de 0,27 % (en poids) en soufre élémentaire contenu dans les 31 échantillons serait celle du soufre d'origine plutôt que celle du soufre produit par altération.

INTRODUCTION

The Waite Amulet minesite, about 20 km north of Noranda, Quebec, has 5.9 million tonnes of sulphide-rich tailings derived from ten orebodies mined in the area from 1929 to 1962. The tailings are 2 to 15 m thick and are in an elevated 41 hectare dam that is undergoing extensive hydrogeochemical investigations to determine the character, sites, and regulating factors of acid generation (Siwik, 1986). This 5-year research program, begun in 1985, is part of the national Reactive Acid Tailings Study (RATS). Noranda Research Centre and CANMET are joint participants in the Waite Amulet study.

To assist in the mineralogical characterization of the Waite Amulet tailings, a series of samples from core WA-20 was examined by the Process Mineralogy Section (Petruk and Pinard, 1986; Jambor, 1986). The hole site is at the steeply sloping edge of the tailings dam and may not be representative of the alteration profile for the main part of the tailings pile. Although additional profiles will be studied as the program advances, priority at the current stage of the investigation was given to an examination of samples collected at piezometric sites. The primary focus of the mineralogical work is the determination of the spatial distribution of alteration and its variations in intensity. As well, the identification of precursor minerals and the species in the alteration products are of importance in interpreting the chemical reactions that have occurred in the past, and are likely to occur if alteration progresses.

SAMPLE PREPARATION

According to Siwik and Dave (1987), core samples of the tailings were obtained using a hollow-stem auger with a 10.8 cm inner diameter, into which was fitted a split-barrel sampler 1.5 m long and 8.25 cm in diameter. For the present study 31 core samples, frozen and sealed in plastic bags, were received from Noranda Research Centre, Pointe Claire, Quebec, on November 20, 1986. Information about drill sites and depth of core collection was not provided. The cores, labelled A-1 to A-31, were temporarily stored in a freezer at CANMET prior to drying. Average sample weight was about 1 kg.

For drying, each sample was removed from its plastic bag and allowed to thaw at room temperature. Subsequent air-drying was accelerated by spreading the pulp over an area of about 0.5 m in diameter on a base of thick brown paper. As drying progressed the pulp was mixed repeatedly and larger lumps were broken to ensure maximum surface exposure. Most samples dehydrated rapidly, but up to 5 days of drying were required for clay-rich or organic-rich material. No significant discoloration or bleaching of the paper base was observed during or at the end of the drying period, thus indicating that the moisture from the samples was unreactive. Likewise, no significant discoloration of the dried tailings pulps was observed. None of the original, uncrushed cores contained megascopic indications of strong oxidation; likewise, no strongly discolored layer indicative of iron oxide-hydroxide alteration was observed in any sample, though a few "iron-stained" layers, 2 to 3 mm thick, were noted to occur erratically.

The air-dried samples were crushed by hand, but not ground, to pass through a 36 mesh Tyler screen (aperture size 425 micrometres). The rela-

tive ease with which the crushing and sieving were accomplished was noted and is summarized in Table 1. A small portion of the +425 μm residual material was collected and bottled as coarse-fraction reference material. Cohesion of the samples was greatest for those noted to contain clay or fine-grained, clay-like textures, and in general the megascopic appearances correlated extremely well with the textures observed in the subsequent microscopic examination (Table 1).

The -425 μm fraction was boxed, and subsequently each sample was again spread on paper, rolled, and cone-and-quartered. A small fraction from each quarter was combined and bottled to use for polished sections, and the remainder of the opposite quarters was combined and bagged. One split was submitted for chemical analysis, and the other was retained as surplus reference material.

Twenty-eight polished sections of the -425 μm samples were prepared using non-aqueous media. Cores A-10, A-11, and A-31 consist wholly of clay-rich material devoid of sulphides, and these samples therefore were not examined microscopically. The clay-rich cores are well-bedded and presumably are from the basal clay zone, 2 to 20 m thick, upon which the tailings were deposited.

Reconnaissance microscopic examination of the 28 polished sections showed that in many the sulphides are very fine-grained, sparse, or both, and that alteration of the sulphides is extremely weak. Because pyrrhotite is the mineral most susceptible to alteration and to assist the recognition of altered grains, an effort was made to obtain a higher yield of the coarser particles of this mineral. Therefore, portions of the fine-grained samples which already had been screened to -425 μm, were rescreened to -270 mesh (aperture size 53 micrometres) and the fines were rejected. The

+53 μm fraction was spread on paper, traversed with a hand magnet to collect the most strongly magnetic fraction, and these magnetic concentrates were mounted in polished sections. Twenty of the 28 samples were treated in this manner, and only 4 failed to show a significant magnetic response; for the 4 non-responsive samples, coarse lumps from the +425 μm reference material were hand-picked and mounted in polished sections. In total, therefore, 48 polished sections of the tailings were examined.

RESULTS

Hand-magnet separations

Screening to remove the fines, and subsequent hand-magnet concentration proved to be an effective method of increasing the abundance and coarseness of pyrrhotite in most of the samples (Fig. 1-4). The few samples that did not respond favourably to this technique were found to consist of fine-grained sulphides dispersed in a fine-grained matrix; coarser particles were absent in the primary material, and thus no concentration was possible.

Textures

Well-developed sulphide-silicate layering was conspicuous in several of the original cores. The layering reflects both a variation in particle sizes, and variations in mineral contents. For example, the layering in some samples was evident because fine-grained beds alternated with coarser-grained beds; in other samples the layering was made conspicuous by the concentration of yellow sulphides into specific beds amidst equigranular material. The layering is considered to be of primary derivation in that it arose from fluctuations in the constitutents added, or unintentionally sorted, during progressive accumulation of the tailings pile.

The samples used for the polished sections and for the chemical analyses invariably represent a blend or homogenization of many layers. Nevertheless, on the basis of microscopic observations of the polished sections, the sulphide-magnetite components of the tailings were classified as fine-grained, intermediate, and coarse (Table 2). The classification is not considered to be particularly significant, but it serves not only to illustrate the very large variation in grain sizes amongst the samples from the piezometric sites, but also provides a contrast with WA-20 core samples (Jambor 1986), none of which would be categorized as fine-grained in this system.

Numerous examples of the textural categories are illustrated in Figures 1 to 4. The fine-grained and coarse-grained textures represent the opposite extremes of the classification, and thus the intermediate category is the broadest and has the greatest diversity in textures. For example, some samples designated as intermediate consist mainly of sulphides of a medium grain size (sample 6, Fig. 2), whereas others have predominantly fine-grained sulphides mixed with scattered coarse grains (samples A-26 and A-27, Fig. 4). These and other variations would permit additional textural subdivisions to be made, but this aspect was not pursued because no ensuing correlation with alteration could be perceived.

Microscopic observations of sulphides and alteration

Microscopic studies of the polished sections in reflected light revealed that the principal sulphide minerals are pyrite and pyrrhotite, and that most sections also contain several grains of chalcopyrite that are typically in locked intergrowths rather than free. Magnetite occurs in variable amounts, either as a major or minor constituent, and only traces of other minerals such as sphalerite, stannite, and native bismuth are

present. These sulphide-magnetite and trace constituents are similar to the assemblages noted in core WA-20 (Petruk and Pinard 1986; Jambor 1986), but the samples from the piezometric sites show more clearly that the variations in mineral proportions simply reflect the primary layering that ensued during tailings accumulation.

Without exception the most distinctive feature of the tailings from the piezometric sites is the absence of significant alteration. In all samples the grain edges of pyrrhotite, which is the mineral most susceptible to alteration, are typically sharp and unreplaced; in several samples, however, scattered pyrrhotite grains with altered rims occur amidst the unaltered grains. These alteration rims indicate that the pyrrhotite was attacked only moderately rather than strongly, and the erratic distribution of the partly altered grains suggests that the alteration was confined to minor layers rather than being pervasive. Similarly, a few goethite rims were observed, but these are extremely narrow and also of erratic distribution. Grain-boundary alterations of pyrite, magnetite, and chalcopyrite are negligible. Table 3 gives the microscopically observed alteration features. Although the pyrrhotite:pyrite:magnetite ratios were estimated for each of the polished sections, these ratios are irrelevent because of the negligible degree of alteration.

X-ray diffractometer scans of clay samples A-10, A-11, and A-31 showed that these samples consist mainly of quartz, plagioclase, chlorite, and muscovite. Calcite was detected in sample A-11. Samples A-10 and A-11 effervesced extremely vigorously when acid was applied, but no reaction was obtained from sample A-31.

Chemical analyses

The principal alteration minerals detected in core WA-20 (Jambor 1986) are goethite, lepidocrocite, marcasite, jarosite, native sulphur, soluble

iron sulphates of the type $FeSO_4.nH_2O$, and simple calcium sulphates of the type $CaSO_4.nH_2O$. Because these alteration products are extremely fine grained and difficult to estimate quantitatively, an analytical chemical approach was deemed to be the most useful in attempting to quantify the abundances of some of the various alteration minerals. The assumptions are that the water-soluble fraction of the tailings contains the $FeSO_4.nH_2O$ and $CaSO_4.nH_2O$ minerals, that the analyses for elemental sulphur reflect the presence of native sulphur, and that the sulphate fraction which is not water-soluble is bound in jarosite. The chemical results obtained from samples of previously studied core WA-20 correlated well with the mineralogical studies, both showing well-defined trends in terms of the intensity of alteration.

The results of the chemical analyses of the core samples from the piezometric sites are given in Table 4. A 2-g split agitated in 100 mL of water was used for the water-soluble sulphate, calcium, and iron determinations. A second 2-g split was used for the determination of total sulphate, and a separate 1-g split was analyzed for elemental sulphur. Details of the preliminary chemical tests and the subsequent analytical procedures are given in an internal CANMET report by J. Hole et al. (1987).

In addition to the chemical results, Table 4 shows the calculated amounts of SO_4 required to use up all of the Ca and Fe in the water-soluble fraction; additional SO_4 not used by the Ca and Fe compounds is tabulated as Remnant SO_4. In most samples the Remnant SO_4 values are fairly low, but in 4 samples (A-2, A-26, A-27, A-28) the values exceed 1 wt. %. It was thought that these samples might contain significant amounts of Na, K, Cu, Mg, or Al soluble salts, but specific analyses for these elements have shown their abundances to be low (Table 5).

The last column in Table 4 gives the value obtained by subtraction of the wt. % water-soluble sulphate from that of total sulphate. This value represents the less soluble compounds such as jarosite. Although the value is generally low, it exceeds 0.3 wt. % in samples A-9, A-17, and A-30. The possible presence of jarosite in samples A-9 and A-17 was indicated by minor oxidation discoloration noted both megascopically and microscopically, and confirmation of the presence of this mineral was obtained by X-ray powder diffracion patterns. No jarosite was observed in sample A-30.

INTERPRETATIONS

All of the samples examined in this study are from below the water table, and all are devoid of significant alteration. The presence of sparse, altered pyrrhotite grains amidst a preponderance of fresh, unaltered grains is an incompatible association that could be interpreted as arising from (a) contamination, or (b) local oxidation. Contamination arises because altered tailings from higher in the hole coat the core barrel and are incorporated as a rind on the main core sample. This effect was very pronounced on two samples of newly received core (not from the piezometric sites and not yet studied), but the contamination was obvious only because of the distinct colour differences between the rind and the main core. This feature was not noticed in the cores from the piezometric sites. In the case of alternative (b), i.e., local oxidation, it was mentioned previously that strongly oxidized cores are absent, but that thin "iron-stained" layers were noted to occur erratically. The thinness of the layers and their erratic presence suggest that each was a surface feature that originated during a minor hiatus in the accumulation of the tailings

These local paleosurfaces were buried subsequently and oxidation ceased. The seemingly incompatible association of altered and unaltered pyrrhotite grains results from blending of the total core sample, thus incorporating the minor, weakly altered zones among the largely unaltered bulk sample.

The second item that merits interpretation is the results of the chemical analyses. In previously studied core WA-20 (Jambor 1986), the calcium sulphate minerals were assumed to have formed from sulphate solutions reacting with calcium derived from lime added to neutralize the surface of the tailings pile. A similar source for the calcium sulphate in the samples from the piezometric sites is possible, but is entirely speculative. An alternative source for calcium is in the reagents added to the flotation circuits; according to Siwik and Dave (1987), the amount of $Ca(OH)_2$ added to the zinc flotation circuit was 0.136 kg/tonne.

The ultimate disposition of other compounds used in the flotation circuits remains one of the major unknown entities in the study of the tailings chemistry. Chief among the added cations is sodium. For example, sodium sulphide and soda ash consumption totalled more than 1.4 kg/tonne in the Waite Amulet copper flotation circuit (Siwik and Dave 1987). Presumably much of this sodium was deposited with the tailings, but no specific mineral carrier has been identified. Similarly, no specific mineral (i.e., native sulphur) has been identified to account for the analytical values obtained for elemental sulphur (Table 4). Certainly the elemental sulphur cannot be attributed to in-situ alteration of pyrrhotite or other sulphides. According to J.E. Dutrizac (oral communication, 1987), elemental sulphur values of the magnitude reported here are not unusual even for unaltered sulphide-rich samples. It also is possible that sodium sulphide,

used as a flotation reagent, contributes to the analytical sulphur values. Thus, the values obtained here for elemental sulphur are interpreted to be principally an indication of "background sulphur" rather than an indication of in-situ alteration.

CONCLUSIONS

1. Microscopic studies of polished sections of the tailings samples from piezometric sites indicate that all samples have negligible amounts of alteration in terms of total sample weight or volume. The presence of sparse altered grains of pyrrhotite amidst unaltered grains is attributed to local surface oxidation that occurred during minor interruptions in the accumulation of the tailings.
2. Chemical analyses indicate that the water-soluble sulphate fraction is low in most samples, and most of this sulphate is bound as $CaSO_4.nH_2O$. The low iron contents of the water-soluble fraction are in accord with the negligible degree of alteration of the sulphides.
3. The fraction of total sulphate that is not water-soluble is low and exceeds 0.3 wt. % in only 3 samples. Most of this relatively insoluble sulphate probably occurs as jarosite, the presence of which was confirmed in 2 of the 3 samples.
4. Three of the cores consist of layered clay that is assumed to be from the floor upon which the tailings were deposited. Two of these clay samples are calcite-rich, thus indicating that the clay is a barrier which is relatively impermeable to penetration by the acid-rich tailings solutions.
5. Contents of elemental sulphur in the samples range from less than 0.01 wt. % to 0.85 wt. %, and the average is 0.27 wt. %. These values are much higher than expected considering the negligible degree of

sulphide alteration. The highest sulphur value occurs in a jarosite-bearing sample, suggesting a possible correlation with alteration. Nevertheless, from the results as a whole it is concluded that the elemental sulphur values obtained for this series of samples are more representative of "background sulphur" than of alteration-derived sulphur.

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Fig. 1. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite (py) and pyrrhotite (po) appear as white to light grey particles; darker grey is magnetite (m).

Sample A-1, magnetic separate. Texture: fine-grained, low sulphide content. Magnetic concentration did not produce a coarser grained sulphide fraction.

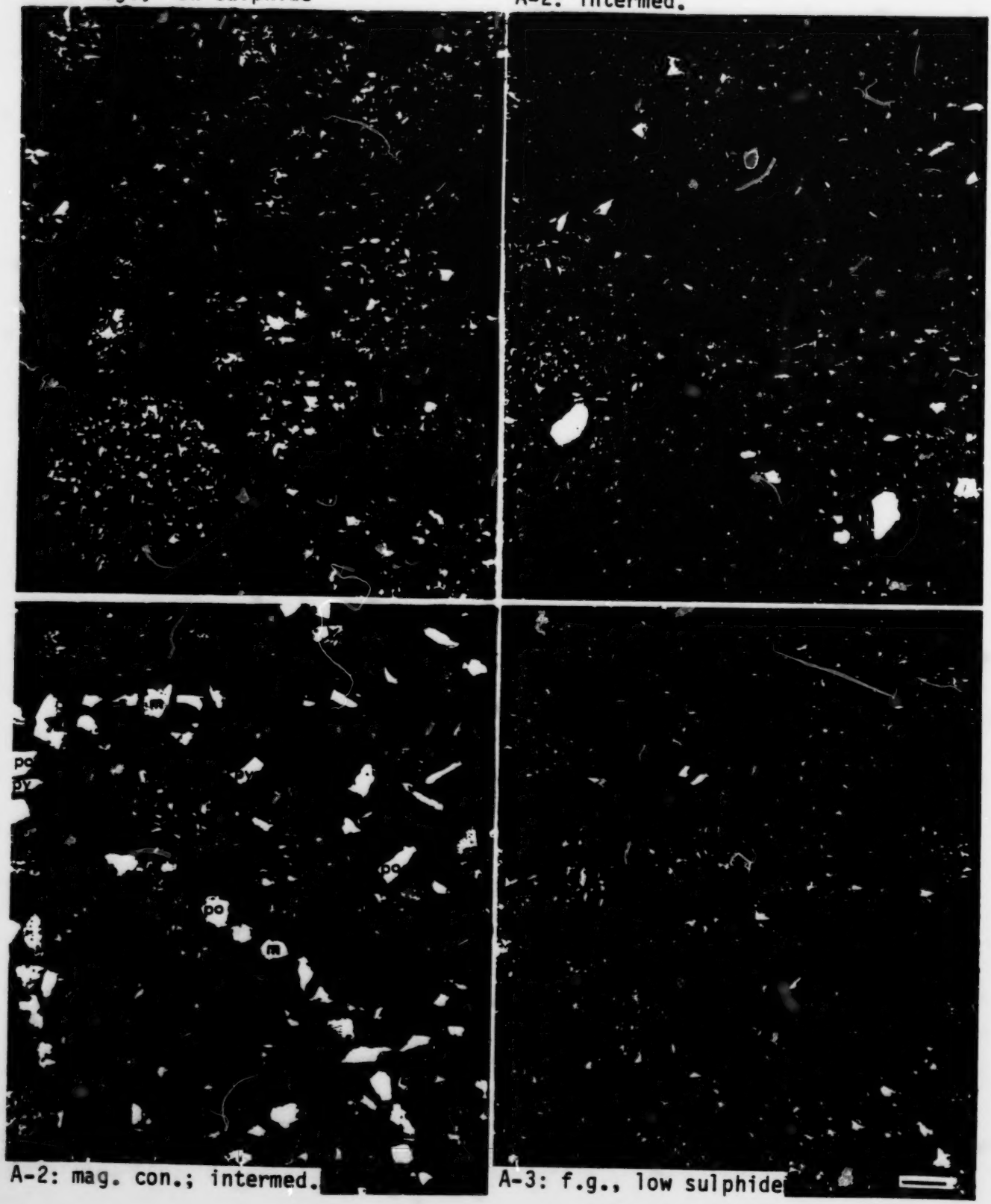
Sample A-2, original fraction. Texture: intermediate; mainly fine-grained sulphides with sparse coarse grains.

Sample A-2, magnetic fraction. Texture: intermediate, coarse grains and clumps containing predominantly medium-grained sulphides have reported to the magnetic concentrate.

Sample A-3, magnetic fraction. Texture: fine-grained, low sulphide content. Magnetic concentration was ineffective.

A-1: f.g., low sulphide

A-2: intermed.



A-2: mag. con.; intermed.

A-3: f.g., low sulphide

Fig. 2. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-4, magnetic separate. Texture: fine-grained sulphides and low sulphide content. Magnetic concentration ineffective.

Sample A-5, original fraction. Texture: intermediate; mainly coarse and medium-grained sulphides.

Sample A-6, original fraction. Texture: intermediate, with sparse coarse sulphides amid medium-grained sulphides.

Sample A-6, magnetic separate. Texture: coarse sulphides and abundant coarse magnetite (m).

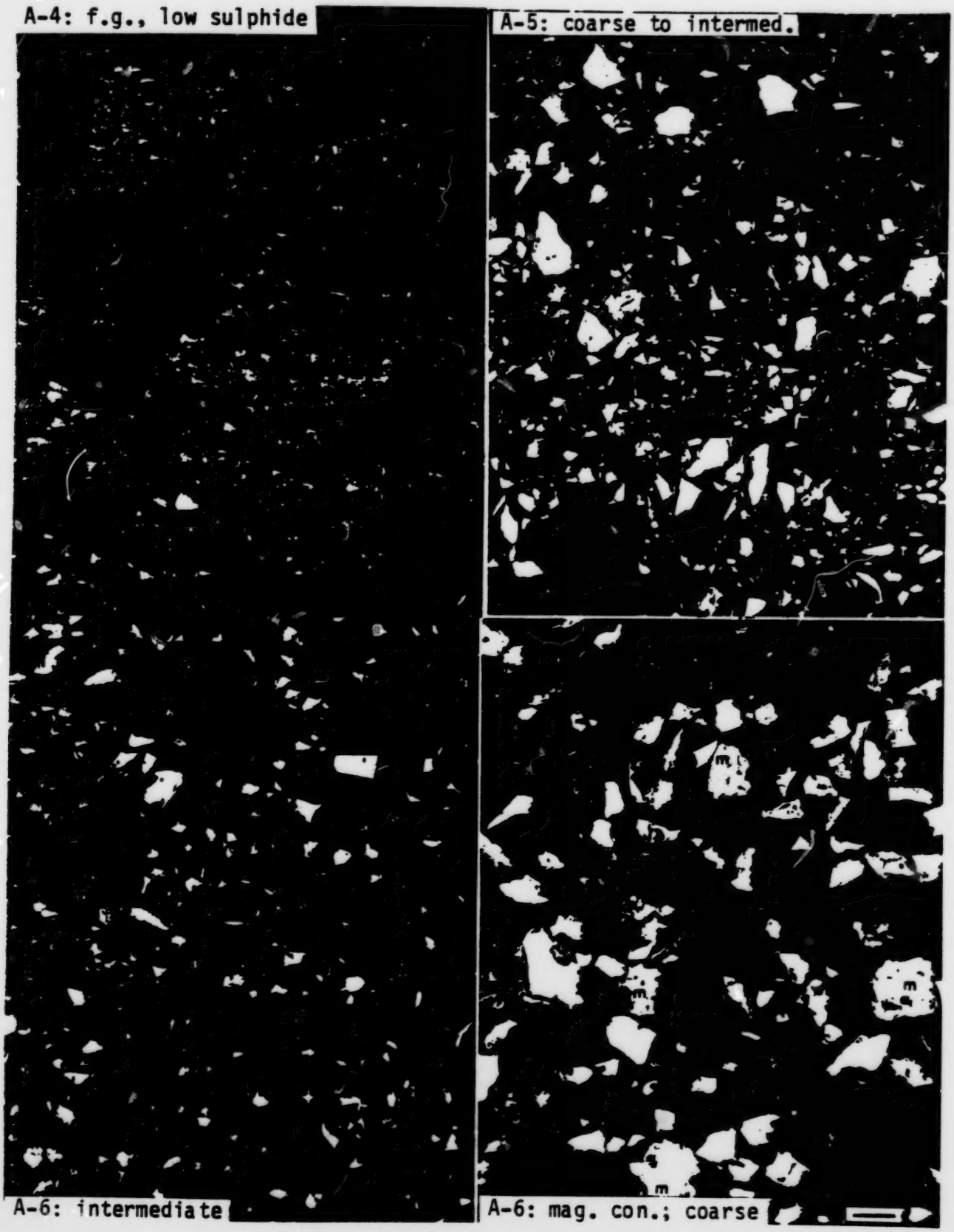

A-4: f.g., low sulphide
A-5: coarse to intermed.
A-6: intermediate
A-6: mag. con.; coarse

Fig. 2

Fig. 3. Photographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-21, original fraction. Texture: coarse-grained.

Samplel A-24, original fraction. Texture: intermediate, with sulphides variable from fine-grained to coarse.

Sample A-22, original fraction. Texture: intermediate, with sulphides predominantly fine-grained, but variable (contrast with sample A-4, Fig. 2).

Sample A-22, magnetic separate. Texture: intermediate.

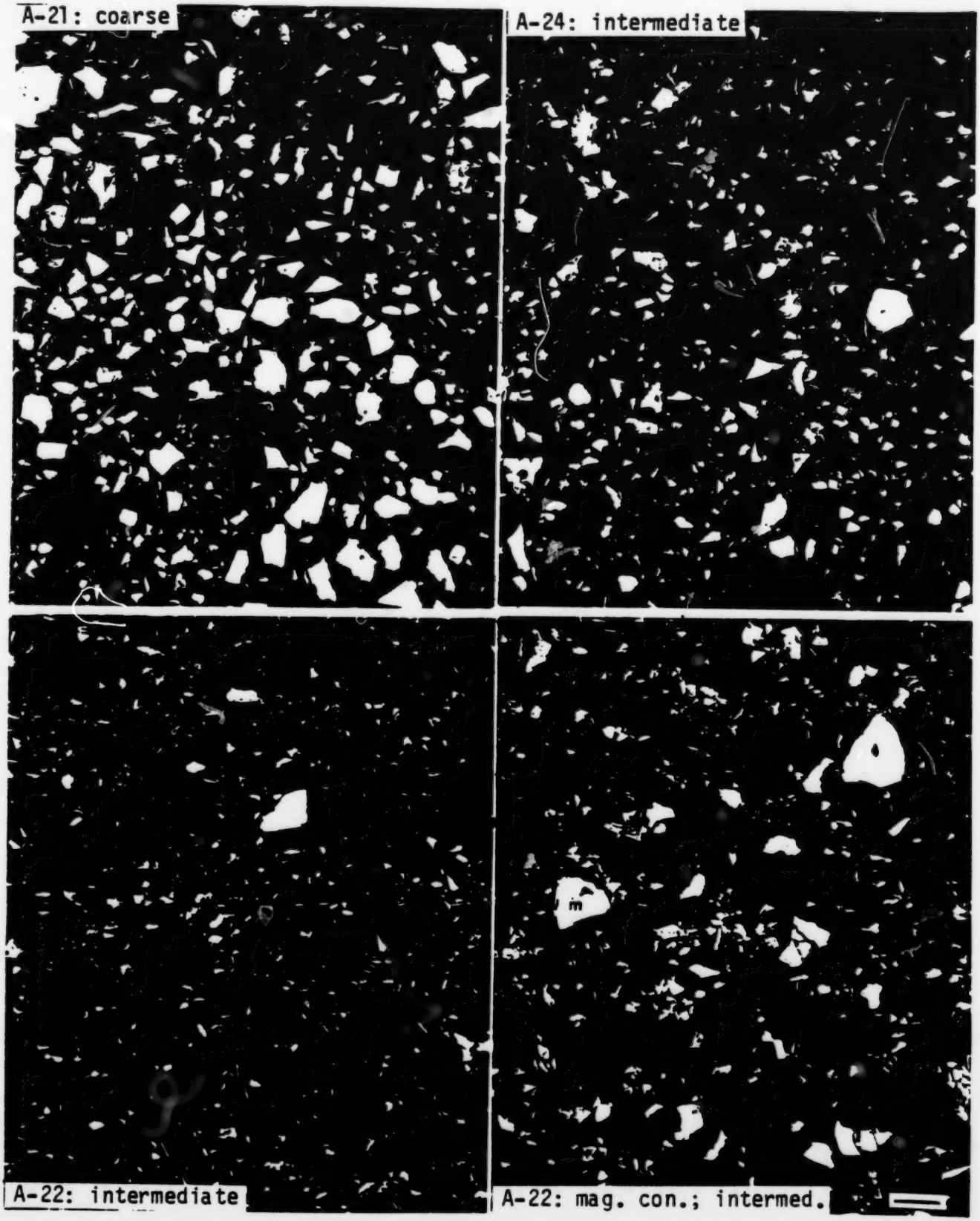

A-21: coarse
A-24: intermediate
A-22: intermediate
A-22: mag. con.; intermed.

Fig. 3

Fig. 4. Photomicrographs of polished sections of Waite Amulet tailings; reflected light, air; all photos at identical magnifications, with bar scale representing 100 micrometres. Pyrite and pyrrhotite appear as white to light grey particles; medium grey is magnetite (m).

Sample A-26, original fraction. Texture: intermediate, mainly fine- and medium-grained with few coarse grains.

Sample A-26, magnetic separate. Texture: intermediate to coarse; concentration was effective.

Sample A-27, original fraction. Texture: intermediate.

Sample A-29, magnetic separate. Texture: fine-grained, low sulphide contents, and ineffective concentration.

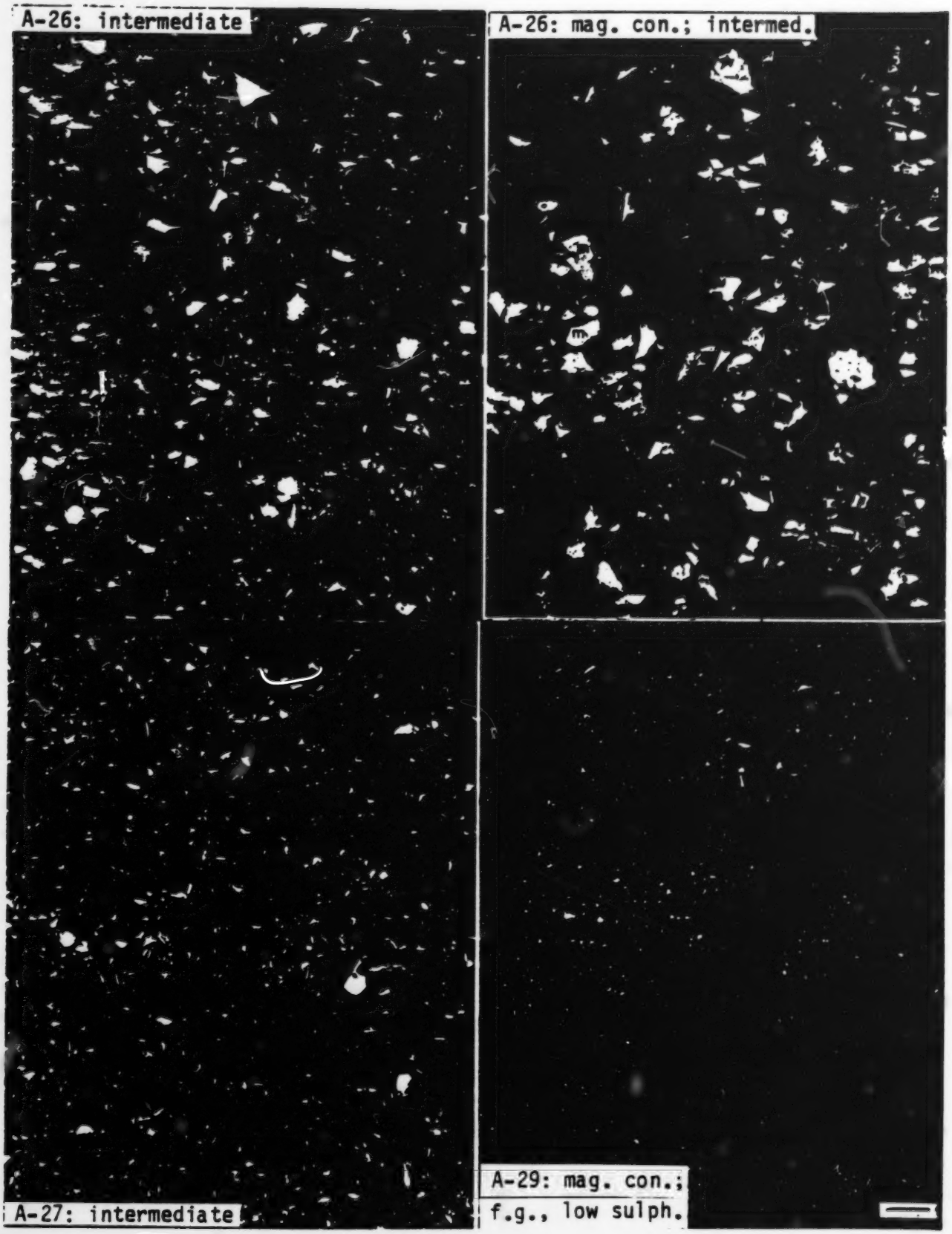

A-26: intermediate
A-26: mag. con.; intermed.
A-27: intermediate
A-29: mag. con.;
f.g., low sulph.

Fig. 4

Table 1. General features of Waite Amulet core samples A-1 to A-31

Sample Number	Megascopic Features; Crushing and Sieving Properties	Microscopic Character
A-1	partly clay-like*; lumps crushed with only moderate difficulty	all fine-grained (Fig. 1)
A-2	almost clay-like; lumps persistent, crushing difficult	mainly fine-grained (Fig. 1)
A-3	almost clay-like; lumps persistent, crushing difficult	fine-grained (Fig. 1)
A-4	almost clay-like; crushed easily	fine-grained (Fig. 2)
A-5	well-layered, high sulphide content; crushed easily	coarse to medium-grained (Fig. 2)
A-6	easily broken and sieved	coarse to medium-grained sulphides (Fig. 2)
A-7	easily broken and sieved	abundant coarse sulphides
A-8	easily broken and sieved	abundant coarse sulphides
A-9	broken and sieved with moderate ease, but some clumps	intermediate grain sizes
A-10	bedded clay; very tough	
A-11	bedded clay; very tough	
A-12	well-layered, coarse-grained sulphides; sieved with great ease	coarse sulphides
A-13	crushed and sieved with ease	coarse sulphides
A-14	crushed and sieved with ease	coarse sulphides
A-15	crushed and sieved with ease	coarse sulphides
A-16	more than 90% organic, mainly a log or old timber	coarse to medium-grained sulphides
A-17	crushed and sieved with ease	coarse to medium-grained sulphides
A-18	abundant organic (peat-like) material; partly clay-like and low in sulphides; difficult to sieve, traces of iron-oxide staining	coarse to medium sulphides, but very sparse
A-19	abundant sulphides; crushed and sieved with ease	coarse sulphides

Table 1. General features of Waite Amulet core samples A-1 to A-31 (cont'd)

Sample Number	Megascopic Features; Crushing and Sieving Properties	Microscopic Character
A-20	abundant sulphides; crushed and sieved with ease	coarse sulphides
A-21	abundant sulphides; crushed and sieved with ease	coarse sulphides (Fig. 3)
A-22	abundant peat, twigs, but sulphides easily sieved	medium-grained sulphides (Fig. 3)
A-23	crushed and sieved easily	coarse sulphides
A-24	sieved very easily; no residual clumps	coarse to medium-grained sulphides (Fig.3)
A-25	similar to A-24	coarse sulphides
A-26	somewhat clay-like, but sieved easily	coarse to fine-grained sulphides (Fig. 4)
A-27	similar to A-26	similar to A-26 (Fig. 4)
A-28	fine-grained, black, almost muddy; crushed and sieved easily	mainly sparse, fine-grained sulphides
A-29	similar to A-28	similar to A-28, but sulphides more abundant (Fig. 4)
A-30	black, muddy, well-layered, but crushed and sieved without difficulty	fine-grained, sparse sulphides
A-31	bedded clay; very tough	

*Clay-like refers to the fine-grained texture rather than to the mineral constituents. Sample A-10, A-11, and A-31, however, are clays rather than merely clay-like.

Table 2. Microscopic textures of Waite Amulet tailings and magnetic concentrates

Sample Number	Textural Classification	General Microscopic Features	Magnetic Fraction
A-1	fine	fine-grained, low sulphide; mainly silicate gangue peppered with sulphides (Fig.1)	no change
A-2	intermediate	mainly fine-grained with scattered coarser grains (Fig. 2)	coarser sulphides increased appreciably (Fig. 2)
A-3	fine	fine-grained, low sulphide (Fig. 1)	fine-grained with sparse sulphide-magnetite grains, 30-100 micrometres across
A-4	fine	similar to A-3 (Fig. 2)	fine-grained with sparse coarse grains
A-5	coarse to intermediate	abundant sulphides, coarse to medium grain sizes (Fig. 2)	not obtained
A-6	intermediate	predominantly medium-grained, free grains (Fig. 2)	coarse (Fig. 2)
A-7	coarse to intermediate	variable, predominantly coarse to medium grains; sulphide content only moderate	coarse
A-8	coarse to intermediate	mainly coarse grains, but clumps with fine-grained sulphides are common	coarse
A-9	intermediate	mainly clumps with medium-grained and fine-grained sulphides; coarse free grains common	intermediate
A-10	clay		
A-11	clay		
A-12	coarse	abundant coarse sulphides	not obtained
A-13	coarse	abundant coarse and medium-grained sulphides	predominantly coarse
A-14	coarse	moderately abundant coarse to medium-grained sulphides	not obtained
A-15	coarse	abundant coarse and medium-grained sulphides	coarse
A-16	coarse	abundant coarse and medium-grained sulphides	coarse
A-17	coarse	abundant coarse and medium-grained sulphides	not obtained

Table 2. Microscopic textures of Waite Amulet tailings and magnetic concentrates (cont'd)

Sample Number	Textural Classification	General Microscopic Features	Magnetic Fraction
A-18	coarse	coarse free grains, many 90-100 micrometres across	coarse
A-19	coarse	coarse sulphides, abundant	coarse
A-20	coarse	coarse sulphides, abundant	not obtained
A-21	coarse	coarse sulphides, abundant (Fig. 3)	coarse
A-22	intermediate	predominantly fine to medium-grained sulphides; sulphides abundant (Fig. 3)	intermediate (Fig. 3)
A-23	intermediate	variable from fine-grained to coarse; sulphides abundant, clumps common	not obtained
A-24	intermediate	abundant, medium to coarse (Fig. 3)	not obtained
A-25	coarse	predominantly coarse grains, moderately abundant	not obtained
A-26	intermediate	coarse to fine-grained sulphides, only moderately abundant (Fig. 4)	intermediate to coarse (Fig. 4)
A-27	intermediate	coarse to medium-grained, abundant (Fig. 4)	intermediate
A-28	fine	mainly fine-grained; sulphide content relatively low; sparse coarse grains	intermediate
A-29	fine	mainly fine-grained; sulphide content relatively low (Fig. 4)	no change
A-30	fine	mainly fine-grained with low sulphide content	fine (some coarse grains)
A-31	clay		

Table 3. Microscopic observations of alteration in tailings from piezometric sites

Sample Number	General Alteration Features	Alteration Intensity
A-1	pyrrhotite edges sharp, intact	negligible
A-2	-	negligible
A-3	thin, grey, partial rims on a few pyrrhotite grains	negligible
A-4	-	negligible
A-5	rim alteration of a few pyrrhotite grains	negligible
A-6	-	negligible
A-7	-	negligible
A-8	-	negligible
A-9	some clumps have pyrrhotite grains with altered rims; local orange (jarosite?) alteration in silicates[1]	local alteration, overall negligible[2]
A-10	clay; carbonate-rich	-
A-11	clay; carbonate-rich	-
A-12	sparse alteration rims on pyrrhotite	negligible
A-13	traces of rim alteration on pyrrhotite	negligible
A-14	a few pyrrhotite grains moderately altered, but otherwise nearly all are fresh	negligible
A-15	several pyrrhotite grains with altered rims; traces of goethite, as rims 1-2 micrometres wide, on silicates	local alteration, overall negligible
A-16	-	negligible
A-17	a few pyrrhotite grains with altered rims	negligible
A-18	similar to A-15	local alteration, overall negligible
A-19	numerous pyrrhotite grains with altered rims 1 to 3 micrometres wide; faint traces of goethite rims on silicates	extremely weak
A-20	traces of rim alteration	negligible

Table 3. Microscopic observations of alteration in tailings from piezometric sites (Cont'd.)

Sample Number	General Alteration Features	Alteration Intensity
A-21	similar to A-19	negligible
A-22	traces of rim alteration	extremely weak
A-23	sparse rims on pyrrhotite; traces of geothite	negligible
A-24	-	negligible
A-25	-	negligible
A-26	traces of rim alteration of pyrrhotite	negligible
A-27	-	negligible
A-28	a few pyrrhotite grains weakly to moderately altered	negligible
A-29	-	negligible
A-30	traces of rim alteration	negligible
A-31	clay sample	negligible

1. Jarosite subsequently confirmed by X-ray powder diffraction patterns.
2. Chemical analyses (Table 4) show this sample to be the highest in sulphate.

Table 4. Chemical analyses of tailings from piezometric sites, and calculated distribution of SO_4

Sample No.	pH	Chem. Anal., Water-Soluble Fraction*			Calculated Distributions (wt%)			Chem. Anal., Whole Sample**		Total SO_4 Minus Water-soluble SO_4**
		Fe	Ca	SO_4	SO_4 as $CaSO_4$	SO_4 as $FeSO_4$	Remnant SO_4	elemental S	total SO_4	
A-1	6.7	<0.01	0.35	1.08	0.84	0.0	0.24	0.52	1.20	0.12
A-2	4.3	0.06	0.31	2.07	0.74	0.10	1.23	0.61	2.28(2)	0.21
A-3	7.5	<0.01	0.55	1.62	1.32	0.0	0.30	0.32	1.71(2)	0.09
A-4	7.9	<0.01	0.37	1.14(2)	0.89	0.0	0.25	0.47	1.14(2)	0.00
A-5	8.3	<0.01	0.13	0.36	0.31	0.0	0.05	0.38	0.39(2)	0.03
A-6	8.4(2)	<0.01(2)	0.12(2)	0.42(2)	0.29	0.0	0.13	0.32	0.42(2)	0.00
A-7	8.7	<0.01	0.10	0.33	0.24	0.0	0.09	0.30	0.36	0.03
A-8	5.5(4)	<0.01(4)	0.27(4)	0.78(4)	0.65	0.0	0.13	0.36	1.05(2)	0.27
A-9	4.3(2)	0.06(2)	0.44(2)	1.98(2)	1.05	0.10	0.83	0.85(2)	2.40(4)	0.42
A-10	8.8(2)	0.06(4)	0.10(4)	<0.03(2)	-		-	0.31(2)	0.03(2)	0.03
A-11	9.0(2)	0.08(4)	0.15(4)	<0.03(2)	-	-	-	0.16	0.03(2)	0.03
A-12	7.6	<0.01	0.07	0.21	0.17	0.0	0.04	0.15	0.24(2)	0.03
A-13	8.5	<0.01	0.14	0.33	0.33	0.0	0.00	0.08	0.33	0.00
A-14	8.7	<0.01(2)	0.08(2)	0.18(2)	0.18	0.0	0.00	0.08	0.27	0.09
A-15	7.9	<0.01	0.09	0.27	0.22	0.0	0.05	0.35	0.33	0.06
A-16	4.6	0.02	0.14	0.54	0.34	0.03	0.18	0.43	0.60(2)	0.06
A-17	4.7(2)	0.09(2)	0.46(2)	1.62(2)	1.10	0.15	0.37	0.14	1.95(2)	0.33
A-18	6.4	<0.01	0.04	0.27	0.10	0.0	0.17	<0.01	0.33	0.06
A-19	4.9	0.09(3)	0.15(3)	0.78(4)	0.36	0.15	0.27	0.21	0.90(2)	0.12
A-20	4.9(2)	0.01(2)	0.19(2)	0.63(2)	0.46	0.02	0.15	<0.01	0.66(2)	0.03
A-21	4.6	0.08	0.03	0.36	0.07	0.14	0.15	0.36	0.39	0.03
A-22	4.4	0.17	0.15	0.81	0.36	0.29	0.16	0.40	1.02	0.21
A-23	6.9	<0.01	0.15	0.48	0.36	0.0	0.12	0.26	0.51(2)	0.03
A-24	6.9	<0.01	0.22	0.66	0.53	0.0	0.13	0.21	0.66(2)	0.00
A-25	6.1	<0.01	0.06	0.24	0.14	0.0	0.10	0.24	0.27(2)	0.03
A-26	4.8(2)	<0.01(2)	0.23(2)	1.08(2)	0.55	0.0	0.53	0.59(2)	1.11(2)	0.03
A-27	6.1	<0.01	0.44	1.26	1.05	0.0	0.21	<0.01	1.26(2)	0.00
A-28	8.1	<0.01	0.40	1.05	0.96	0.0	0.09	<0.01	1.20(2)	0.15
A-29	7.9	<0.01	0.36	0.81	0.81	0.0	0.00	<0.01	0.93(2)	0.12
A-30	7.7(4)	<0.01(4)	0.30(4)	0.63(4)	0.63	0.0	0.00	0.19	1.08(2)	0.45
A-31	7.0(4)	0.02(4)	<0.01(4)	0.03(4)	-	0.03	0.00	<0.01	0.03(3)	0.00

*Water-soluble at room temperature; values are in wt %.
**Wt %. Numbers in parentheses refer to replicate determinations of separate splits.

Table 5. Chemical analyses of samples containing excess water-soluble sulphate*

Sample	Original (wt %)				New Analysis (wt %)							
No.	pH	Fe	Ca	SO_4	pH	Fe	Ca	SO_4	Na	K	Cu	Mg	Al
A-2	4.3	0.06	0.31	2.07	4.1	0.12	0.45	2.40	<0.01	0.02	0.03	0.06	0.03
A-26	4.8	<0.01	0.23	1.08	4.4	0.04	0.26	1.11	<0.01	0.09	<0.01	0.06	<0.01
A-27	6.1	<0.01	0.44	1.26	5.5	<0.01	0.42	1.29	<0.01	0.04	<0.01	0.03	<0.01
A-28	8.1	<0.01	0.40	1.05	7.6	<0.01	0.50	1.32	0.01	0.02	<0.01	0.09	<0.01

*Refers to excess water-soluble sulphate that cannot be accounted for in terms of simple calcium sulphate or ferrous sulphate compounds.